Augmentation Awards for Science and Engineering Research Training Program
AASERT
Final Technical Report
1 July 1995 through 30 June 1998
F49620-95-1-0465

Project Title:	AASERT 95 (BMDO) Routing of optical data via spatial-spectral Holographic Devices
Principal Investigator:	Thomas W. Mossberg Professor of Physics University of Oregon Eugene, Oregon 97403 Phone: 541-346-4779 Fax: 541-346-4791 email: twmoss@oregon.uoregon.edu
Institution:	University of Oregon 5215 University of Oregon Riverfront Research Park 1600 Millrace Drive, Suite 106 Eugene, OR 97403-5215
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Executive Summary

This ASSERT research contract provided student support funds necessary to expand the scope of two successive primary AFOSR contracts (F49620-92-J-0443 and its renewal F49620-96-1-0259). During the course of the supported work, the first experimental demonstrations of swept-carrier time-domain optical memories were completed with full results published in the scientific literature. Swept-carrier memory utilizes the intrinsic absorptive frequency selectivity displayed by many materials, especially when cryogenic, to dramatically enhance optical storage densities and potentially achieve ultra-high memory input/output rates. The swept-carrier approach to utilizing frequency selectivity combines the best features of frequency-selective storage methods proposed earlier. Succinctly put the swept-carrier concepts allows for the complete utilization of the frequency multiplicity available in a specific material without constraining the data rate employed. Earlier frequency-selective memory concepts could only achieve full material utilization in available materials by employing impractically high or low data input/output rates. The ability to fully utilize storage materials with a wide range of parameters means that operating temperatures of frequency-selective memories may more easily be pushed to higher values. Experimental demonstration of single-sideband optical data storage and bit-rate shifting using frequency-selective materials has also been provided. As part of the supportive development work on this contract, a simple and easily fabricated external cavity diode laser capable of unprecedentedly high tuning rates was developed. Also, a new laser frequency stabilization method was developed and patented. This stabilization method provides for extreme frequency agility combined with maximal frequency stability down to the Fourier transform limit

Summary

Spatial-spectral holographic techniques provide the potential for high speed, high density, storage of real time optical waveforms without electronic conversion - fully optical memory. Essentially the same process can be employed to implement real time processing (convolution, cross-correlation) of optical signals up to the high Gigahertz data regime. In order for the processes to be useful, it is highly desirable that operations be cascadable and distributable. These processes require minimal insertion losses. For this reason, a successful effort was undertaken to identify those regimes in which spectral holographic devices could operate with minimal (and in fact sometimes negative) insertion loss.

Work on the energy efficiency and power of spatial-spectral holographic signals was focused on simple photon and stimulated echo effects believed to be representative of behaviors to be expected in quite general situations. Two different scenarios were studied. In the first case, the generation of spatial-spectral holographic signals in single-pass media was considered. It was found that photon echo energy efficiencies, i. e. energy of output signal divided by energy of information-containing input signal, could exceed unity. In order to achieve this result, the material sample had to be chosen so as to be optically thick, i. e. in the absence of optical saturation, resonant power transport through the sample should fall in the e^{-3} or lower regime. Prior to the present work, it was believed by those working in the field that spatial-spectral holographic signals were optimized when sample absorption was on the order of 1/e. The present results show optimization in a very different regime. It was also found that non-information containing input fields had to be chosen and configured to provide uniform excitation across the spectral bandwidth of the input signal and to

provide specific degrees of sample excitation, i. e. specific input pulse areas. Finally, it was found that non-information-containing input pulses, having a spatial profile uniform across that of the input signal, are crucial in maximizing output signal intensity. A surprising result of the present work is that spatial-spectral output signals can actually be larger than input signals, i. e. the devices are capable of optical gain. In the application space, this attribute will be important as other problem areas involving frequency-selective recording materials (particularly related to necessary low material temperatures) are solved.

Another approach to obtaining large spatial-spectral signal sizes was explored. In this approach, a weakly absorbing sample is placed in a moderately high finesse cavity wherein the material absorption raised to a power equal to the cavity finesse was on the order of e^{-3} or lower. Use of the cavity approach allows one to use recording materials wherein intrinsic high absorptivity is not possible. It is found that the cavity method is effective in producing signal sizes that are comparable or even larger than those obtained in single-pass media. The cavity method of enhancing spatial-spectral signal size is also important in that the cavity acts as a power buildup device thereby lowering laser powers needed to effectively interact with the non-linear frequency-selective materials. Furthermore, in the cavity approach to spatial-spectral signal enhancement, the low intrinsic absorptivity of the recording material makes it possible to subject it to uniform absorption along its length. Spatially uniform excitation makes it possible for more control over the processing functions implemented in device applications since they are often sensitive to the absolute power levels of the input signals involved.

The reported studies of spatial-spectral holographic energy efficiency in cavities have been the impetus to explore a broader set of questions in coherent light-matter interactions. Rare-earth

atoms doped into inorganic crystals exhibit ultraslow decohering rates at cryogenic temperatures. In fact the decohering rates observed in cryogenic rare-earth doped systems are the smallest optical decohering rates ever observed in condensed phase materials. Recently, with the intense interest in quantum computing and related issues, it has become imperative to find and understand slowly decohering optical systems and to understand their radiative interactions. In the reported studies of spatial-spectral holographic signal size in cavities, it was necessary to construct a cavity system at cryogenic temperatures having a rare-earth-doped sample in its interior. The rare-earth-ion + cavity system is unique in that the ionic decohering rate sets the longest time-scale in the problem. Preliminary observations indicate unique new cavity-mediated light-matter interactions. Detailed study of these effects is being funded by a successor contract to the one being reported upon here.

Stable, yet frequency agile lasers were necessary to support the work described above. Such lasers are useful in multiple contexts and application areas many having nothing to do specifically with spatial-spectral holography. To perform the work reported here, development of stable, yet frequency agile lasers was necessary. To this end, a new and innovative method of cw laser stabilization was developed. In this method, sample laser output is split, one part is frequency shifted by an acousto-optic (AO) device, while the other part is delayed by several microseconds in optical fiber. The light is recombined producing a heterodyne beat signal. If the laser frequency is stable, the heterodyne beat frequency is simply the AO frequency offset introduced. On the other hand, if the laser is changing in frequency, the heterodyne frequency is the AO offset modified by an additive factor proportional to the time derivative of the laser's frequency. A phase-locked-loop is used to convert variations in heterodyne beat frequency to an error signal proportional to the laser frequency's time rate of change. The error signal is then used to zero that rate and thereby lock the

laser's frequency. The important point is that the laser frequency is stabilized without an external frequency reference. Moreover, the feed back circuitry can be configured to accept control inputs that provide for programmed excursions in laser frequency while the heterodyne feedback loop provides continuous elimination of unwanted FM noise. The unique character of the locking method has led to a patent application. The U. S. Patent office has already responded with a notification that the claims submitted have been allowed.

Supported Personnel:

Mr. Tsaipai Wang, graduate student (parent grant)

Mr. Christoph Greiner, graduate student (parent grant)

Mr. Bryon Boggs, graduate student (ASSERT)

Dr. Thomas W. Mossberg, Professor of Physics (parent grant)

Publications:

1. "Single-sideband spectral holographic optical memory," H. Lin, T. Wang, and T. W. Mossberg, Opt. Lett. 21, 1866 (1996).
2. "Optical waveform processing and routing with structured surface gratings," Babbitt, W. R., and Mossberg, T. W., Opt. Commun. **148**, 23 (1998).
3. "Simple high-coherence rapidly tunable external-cavity diode laser," Boggs, B., Greiner, C., Wang, T., Lin H. and Mossberg, T. W., Optics Lett. **23**, 1906-8 (1998).
4. "Experimental observation of photon echoes and power-efficiency analysis in a cavity environment," Wang, T., Greiner, C., Mossberg, T.W., Optics Lett. **23**, 1736-8 (1998).

5. “Laser frequency stabilization by means of optical self-heterodyne beat-frequency control,” Greiner, C., Boggs, B., Wang, T. and Mossberg, T. W., Optics Lett. **23**, 1280-2 (1998).

6. “Photon echo signals: beyond unit efficiency,” Wang, T., Greiner, C., Mossberg, T. W., Optics Commun. **153**, 309-13 (1998).

Interactions/Transitions:

a. Conference Presentations:
Contributed:

Optical Heterodyne study of frequency-swept, external-cavity, diode laser coherence properties, T. Wang, H. Lin, and T. W. Mossberg, OSA/ILS 1996 Annual Meeting, Oct. 20-26, 1996, Rochester, NY.

“Experimental observation of efficient photon echo in optically thick media;” Wang, T., Greiner, C., Bochinski, J. R. and Mossberg T. W.; Presentation at the 1998 Annual Meeting of the Optical Society of America, session code TuQ5.

“Laser frequency stabilization by means of optical self-heterodyne beat-frequency control;” Greiner, C.; Boggs, B.; Wang, T.; Mossberg, T.W.; Technical Digest. Summaries of Papers presented at the Conference on Lasers and Electro-Optics. Conference Edition, 1998 Technical Digest Series, Vol.6 (IEEE Cat. No.98CH36178).

“Cavity enhancement of coherent transient signals;” Wang, T., Greiner, C. and Mossberg, T. W.; Presentation at the 1997 Annual Meeting of the Optical Society of America, session code ThKK4.

“Experimental demonstration of temporal-waveform-controlled spatial routing of optical beams via spatial-spectral filtering,” Wang, T., Lin H. and T. W. Mossberg, CLEO '96, Summaries of papers presented at the Conference on Lasers and Electro-Optics, Vol.9. 1996 Technical Digest Series, Conference Edition (IEEE Cat. No.96CH35899), p. 544, 349-50.

Wang, T.,Lin H. and Mossberg, T. W., “Single sideband data retrieval using swept-carrier optical memory,” CLEO '96. Summaries of Papers Presented at the Conference on Lasers and Electro-Optics, Vol.9, 1996 Technical Digest Series. Conference Edition (IEEE Cat. No.96CH35899), p. 544, 196-7.

Invited:

Cavity-enhanced Photon Echoes, Air Force Workshop on Persistent Spectral Holeburning, T. W. Mossberg, Big Sky Montana, March 1997.

Persistent Spectral Holeburning and Applications, T. W. Mossberg, Rare-Earth Research Conference, Duluth, MN, July 1996.

Persistent Spectral Holeburning and Applications, T. W. Mossberg, Persistent Spectral Holeburning Conference, Brainerd, MN, Sept. 1996.

Time-Domain Spectral Holographic Memory, T. W. Mossberg, OSA/ILS 1996 Annual Meeting, Oct. 20-26, 1996, Rochester, NY.

Time-Domain Spectral Holographic Memory, T. W. Mossberg, IEEE LEOS Annual Meeting, Nov. 18-21, 1996, Boston, MA.

b. Consultative and advisory functions to other laboratories and agencies: None

c. Transitions: Supported work at the University of Oregon is being performed in collaboration with researchers at Templex Technology Corporation of Eugene, Oregon. Templex is involved in the commercialization of time-domain frequency-selective memory devices and content-controlled all-optical routers and switches.

New Discoveries:

We have shown through simulation that unexpectedly large coherent transient signals can be generated in optically thick recording materials. Output signals larger than input data pulses are predicted.

A new laser frequency stabilization method which we refer to as "derivative locking." In this method, a fiber interferometer is used to produce a beat signal proportional to a laser's

frequency rate of change. Phase-Locked Loop electronics convert the beat signal variation to feedback maintaining the laser frequency fixed. The method requires no spectral reference and thus supports frequency agility combined with spectral stability.

Honors/Awards:

T. W. Mossberg

Lifetime:

Fellow Optical Society of America

Fellow American Physical Society

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6. AUTHOR(S)
Mossberg, Thomas W.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Oregon, 5215 University of Oregon
Riverfront Research Park, 1600 Millrace Drive,
Suite 106, Eugene OR 97403-5215

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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14. ABSTRACT
This ASSERT award provided funds necessary to incorporate additional student resource into a primary AFOSR-sponsored research program. During the funding interval, the first laboratory demonstration of swept-carrier frequency-selective optical memory was realized. Additional results include the development of a frequency-agile narrow linewidth external cavity diode laser and a recently-patented laser-frequency-stabilization method that is compatible with extreme frequency-agility.

15. SUBJECT TERMS
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